COMMENTARY

Ecosystem Health and Its Measurement at Landscape Scale: Toward the Next Generation of Quantitative Assessments

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ABSTRACT

The purpose of this paper is twofold: (A) to describe the challenges of reporting on changes in ecosystem health at landscape scales, and (B) to review the statistical and mathematical techniques that allow the derivation of landscape health assessments from a variety of data consisting of remote sensing imagery, demographic and socioeconomic censuses, natural resource surveys, long-term ecological research, and other geospatial information that is site specific.

We draw upon seven innovative and integrative concepts and tools that together will provide the next generation of ecosystem health assessments at regional scales. The first is the concept of ecosystem health, which integrates across the social, natural, physical, and health sciences to provide the basis for comprehensive assessments of regional environments. The second consists of innovative stochastic techniques for representing human disturbance and ecosystem response in landscapes, and the corresponding statistical tools for analyzing them. The third constitutes representation of spatial biocomplexity in landscapes through application of echelon analysis to assessment. The fourth concerns innovative combination techniques of upper-echelon-based spatial scan statistic to detect, delineate, and prioritize critical study areas for evaluating and prioritizing causal factors and effects. The fifth involves the capability of comparing and prioritizing a collection of entities in light of multiple criteria, using poset mathematics of partial order with rank frequency statistics, to provide multicriterion decision support. The sixth lies in extending data mining and visualization techniques to determine associations between geospatial patterns and ecosystem degradation at landscape scales. The seventh encompasses comprehensive studies conducted on different types of regional ecosystems.

Our focus is to show how the integration of recent advances in quantitative techniques and tools will facilitate the evaluation of ecosystem health and its measurement at a variety of landscape scales. The challenge is to characterize, evaluate, and validate linkages between socioeconomic drivers, biogeochemical indicators, multiscale landscape pattern metrics, and quality of human life indicators. Initial applications of these quantitative techniques and tools have been with respect to regions in the eastern United States, including the U.S. Atlantic Slope and mid-Atlantic region.

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1. MEETING THE CHALLENGE OF ASSESSING LANDSCAPE CHANGE

Degradation of ecosystems is pervasive at local, regional, and biospheric scales (Arrow *et al.* 1995; Vitousek *et al.* 1997). Remotely sensed data of the earth's surface along with other sources of data offer enormous potential to assess changes in the health of the earth's ecosystems, identify risks of further degradation, and determine opportunities for restoration. Yet, little of this potential has been realized. Partly, this is owing to the lack of an appropriate conceptual framework to capture the biocomplexity of the system, including the socioeconomic, biophysical, and human health dimensions. And partly, it is owing to the lack of analytical methodologies sufficient to represent and predict the underlying biocomplexity (Geoghegan *et al.* 1998; Michener *et al.* 2001).

It is well known that human induced stressors progressively have impaired the capacity of ecosystems to provide essential services to humanity (Daily 1997). The biocomplexity of impairment manifests itself through a wide variety of characteristics, including generally reducing terrestrial primary productivity, biodiversity, habitat suitability for endemic species, and ecological integrity, while increasing fragility, vulnerability, resiliency, etc. The statistical and mathematical tools proposed herein, combined with a new generation of data availability, allow a description of changes in biocomplexity both spatially and temporally. In order to make ecosystem health assessments effective, these expressions must be captured rapidly, comprehensively, and economically. These requirements can potentially be achieved through utilization of advanced remote sensing capabilities in conjunction with available geospatial databases.

Attempts to assess the health of regions comprehensively, considering the condition of humans as well as flora and fauna, have experienced several limitations: the lack of essential synoptic data, assessments based on field studies generally constrained to small areas employing classical statistical tests (e.g., Wichert & Rapport 1998), failure to integrate across humanistic and naturalistic dimensions (Epstein & Rapport 1996), and the lack of appropriate analytical methods (Patil & Myers 1999; Patil 2002a) capable of capturing the high degree of complexity inherent in these regional systems.

These barriers can be breached by marrying the concept of ecosystem health with advances in statistical and computational methodologies for representing the spatial and temporal complexity of key indicators of ecosystem health on a landscape basis (Johnson *et al.* 2002; Patil et al. 2000a, b; Patil & Taillie 2001b).

Our approach will contribute to model-based reproducible automated assessment and management of ecosystem health, distress, and degradation. We call this quantitative toolbox the MARMAP (Multiscale Advanced Raster MAP) system (Johnson *et al.* 2002; Patil 2000; Patil 2001b,c,d; Patil 2002b; Patil *et al.* 2002). Details are available on our website (http://www.stat.psu.edu/~gpp/newpage11.htm) together with 35 related publications, describing the methods, tools, case studies, outcomes, and references.

The MARMAP methods and tools have come about as a result of earlier research with agencies concerned with watershed ecosystem health-related issues and approaches involving a multiplicity of empirical geospatial data and remote sensing information over the mid-Atlantic region, Pennsylvania, China, and Italy. The problems and solutions required a toolbox of appropriate geoinformatic inferential capabilities. MARMAP is evolving in response to this need. This paper sketches how MARMAP can be put to effective use to assess ecosystem health at landscape scales.

2. INDICATORS OF ECOSYSTEM HEALTH AT LANDSCAPE SCALE

WHAT CONSTITUTES ECOSYSTEM HEALTH?

A healthy ecosystem has been defined as one that is free from distress and degradation, maintains its organization and autonomy over time, and is resilient to stress (Rapport *et al.* 1998). Ecosystem health can be assessed by indicators of vigor (productivity), organization, and resilience (Mageau *et al.* 1995; Costanza *et al.* 1998a,b).

Ecosystem health assessments, generally based on extrapolation from limited field data, provide empirical support for the use of such indicators for monitoring health (and conversely, degradation) in field situations (Hilden & Rapport 1993; Rapport & Whitford 1999; Rapport *et al.* 2000).

ASSESSING ECOSYSTEM HEALTH AT REGIONAL SCALES

The potential for multiple dynamic stable states of both natural and human-dominated ecosystems complicates the task of determining the extent to which ecosystem structure and function have been altered by human activity. Nonetheless, numerous studies leave little doubt that ecosystem degradation has occurred in many systems well documented by the appearance of "Ecosystem Distress Syndrome" (Rapport & Whitford 1999). This documentation enables examining groups of highly selected indicators and comparing their values with norms established for reference ecosystems.

Rapport *et al.* (1985) identified recurrent features of stressed terrestrial systems, including impairments in primary productivity and nutrient cycling, reduced resilience, altered community dominance favoring "r"-selected species (shorter reproductive cycles, smaller size), increases in non-native species (exotics), increased disease prevalence, increased instability in component populations, reduced biodiversity, etc. These properties have been validated in a number of subsequent case studies (Hildén & Rapport 1993; Rapport & Whitford 1999). Using proxies for the key signs of ecosystem distress (e.g., biodiversity, community dominance, sediment loads, nutrient status of receiving waters) and relating these to appropriate synoptic data, provide a quantitative portrait of ecosystem health for each landscape context.

RELATIONSHIP OF ECOSYSTEM DISTRESS TO SOCIOECONOMIC ACTIVITY

A critical element of biocomplexity entails delineating the complex temporal and spatial relationships between socioeconomic variables and ecosystem dynamics. Improved understanding of the relationships that exist between ecosystems and socioeconomic systems across time and space is essential to the design of economic, environmental, and natural resource policies that aspire to achieve sustainable outcomes with high levels of ecosystem health and quality of human life (Abler *et al.* 2000; Bockstael 1996; Shortle & Horan 2001; Deacan *et al.* 1998; Pickett & Rogers 1997; Polasky *et al.* 2001; Vernberg *et al.* 1997; Wu 2001). The necessary assessments must systematically integrate indicators of ecosystem health, discussed above, with indicators of the quality of human life and the functioning and structure of socioeconomic systems (Bockstael 1996; Conforth 1997; Michalos 1997).

3. ECOSYSTEM HEALTH, DISTRESS AND DEGRADATION OF WATERSHEDS AT LANDSCAPE SCALE

The mid-Atlantic region studies demonstrate the feasibility and practicality of ecosystem health assessments. This area provides an ideal case study because it is an ecoregion that is rich in synoptic data, and it contains many of the geographical elements found in the eastern United States and other temperate regions (Brooks *et al.* 2001). At least five major ecoregions occur in the mid-Atlantic region (i.e., Coastal Plain, Piedmont, Ridge and Valley, Unglaciated Plateau, and Glaciated Allegheny Plateau). These ecoregions extend in all directions increasing the utility of our findings to adjacent regions. The mid-Atlantic region also contains three major river drainages that vary in their physical, chemical, and biological attributes (i.e., Delaware, Susquehanna, and Ohio). A variety of land use types and patterns have evolved in the region, including, densely forested, high-density urban, agricultural, mined, and mixed land uses. Thus, the mid-Atlantic region's natural and human-induced landscapes, gradients, and boundaries provide a wealth of options to explore.

For example, Pennsylvania watersheds have been mapped at scales ranging from 102 units for the State Water Plan to 9,855 units for individually named streams. These watershed units have been studied from diverse perspectives including non-point pollution, groundwater pollution potential, land cover, and animal habitats (Johnson 1999; Johnson *et al.* 2001a,b; Johnson *et al.* 2002; Johnson & Patil 1998; Myers *et al.* 2000; Patil *et al.* 2000a,b). Pennsylvania watersheds vary in their ecology, geology, hydrology, degree of human influence, etc. Representing this complexity synoptically in a format that enables one to address questions of ecosystem health, integrity, and resilience is our key challenge and goal. Using the collective data from the mid-Atlantic region, we confront the following types of questions in this context: What is the health status of a particular watershed and how does this compare with a similar but less stressed system? To what degree is ecosystem degradation associated with cumulative effects from population growth and economic development within the watershed? Do changes in spatial biocomplexity of key indicators of ecosystem distress serve as an early warning sign of loss of resilience at regional scales? Which watersheds show the greatest degree of fragmentation? Do these watersheds also indicate a loss of ecosystem services, such as water quality and habitat? Is the degree of fragmentation within watersheds correlated with the loss of ecosystem goods and services as measured by synoptic data on water quality, soil erosion, biodiversity, etc.?

There are relatively few synoptic, biological data sets available for large geographic regions. To represent features of biological diversity in landscape analysis, we can use habitat distributions for all vertebrates based on models from the National GAP Analysis Program for Pennsylvania (Myers *et al.* 2000) and adjacent states. In addition, we have developed and used bird guilds as indicators of ecological integrity over regional landscapes (i.e., Bird Community Index (BCI), O'Connell *et al.* 1998; O'Connell *et al.* 2000; Johnson *et al.* 2002). The BCI is a multimetric index of upland ecological integrity in the mid-Atlantic highlands that has been extended to other ecoregions in the mid-Atlantic for forested-, agricultural-, and urban-dominated landscapes (O'Connell *et al.* 1998). For aquatic parts of ecosystems, we can use fish models from the aquatic portion of GAP (Myers *et al.* 2000) and available fish surveys from state and regional bioassessment surveys (e.g., Environmental Monitoring and Assessment Program, EMAP 2000). Data from the EMAP (2000) streams assessment are available for over 500 reaches in the region. We also have at our disposal the data warehouse, Pennsylvania Spatial Data Access (PASDA), a publicly funded web-based repository of geospatial data layers and metadata for Pennsylvania, often with extensions of coverages for areas in neighboring states.

4. ECOLOGIC AND SOCIOECONOMIC INDICATORS FOR INTEGRATED ASSESSMENT

Every place on the planet has associated sets of naturalistic and humanistic characteristics that define its health in the broadest sense of the word. Climatic, geologic, hydrologic, biologic, and human-induced factors all combine to produce a set of ecological, economic, and social functions that characterize a place and determine its biocomplexity and socioeconomic complexity, as well as the extent to which social and ecological relationships are integrated. The complex array of natural and human factors in a region can be characterized by sets of socioeconomic and ecological indicators describing these zonal systems and their overlapping areas of tension (Conforth 1997). By systematically collecting and examining such indicators, the patterns that emerge as these places are aggregated into landscapes can be described quantitatively. Wherever possible, we search for indicators that reflect on current ecosystem and socioeconomic conditions, socioeconomic drivers of ecosystem change, and indicators of ecological and economic sustainability (Horan *et al.* 2000; Michalos 1997).

Many indicators for landscape analyses are available for the mid-Atlantic region and have been catalogued by the Atlantic Slope Consortium (Brooks *et al.* 1998; Brooks *et al.* 2001). These spatial patterns can be explored within homogeneous regions and across gradients and abrupt boundaries in the region. Similarly, a range of data sources is available for developing indicators of socioeconomic conditions and quality of life for various spatial units. A major source is U.S. Census Bureau data, collected for census tracts, census blocks, zip codes, and counties, covering a range of variables for describing populations and economic structure and performance. The U.S. Department of Agriculture provides a range of socioeconomic indicators for rural areas (http://www.ers.usda.gov/data/RuralMapMachine). Importantly, methods have also been developed for constructing indicators of environmental amenities, an increasingly important determinant of the quality of life, from routine data sources (Deller *et al.* 2001).

The same geographic elements that are used to define an ecoregion also influence how patterns of historic and current land use develop. Human impacts, then, alter the original natural potential of an area. Natural and human factors are inexorably linked and together define the ecosystem health and quality of life for a place. The interactive tension between them is analyzed by identifying socioeconomic and ecological indicators that describe the separate systems, together with an additional set of indicators that captures the complexity of the relationships between them (Conforth 1997; Michalos 1997).

Although spatial landscape analyses have been conducted for years, it has been difficult to compare different locations when using multiple indicators simultaneously. However, with the application of insightful sophisticated quantitative methods, it is possible to create truly integrative measures that characterize the synergistic relationships among landscape patterns and indicators. In particular, we explore the techniques described here for addressing multiple indicators, partial orderings, and multicriterion decision support along with echelons of spatial variation. We examine the resultant patterns within at least four distinct ecoregions, i.e. Piedmont, Ridge and Valley, Unglaciated Plateau, and Glaciated Allegheny Plateau (Brooks *et al.* 2001), across boundaries of these same ecoregions, along rural-urban gradients (e.g., from Philadelphia to the northwest), across landscapes with forested, agricultural, urban, and mixed land use patterns, and within and across watershed boundaries for the Delaware, Susquehanna, and Ohio drainage basins (Brooks *et al.* 2001). This approach allows one to search for and define consistent and recognizable landscape patterns, while at the same time, allowing one to define a set of reference conditions to understand the consequences, both favorable and unfavorable, that human actions have on biocomplexity. Data envelopment analysis techniques may also help explore sources of variation in the ecological and socioeconomic performance of regions.

5. MATHEMATICAL, STATISTICAL, COMPUTATIONAL, AND VISUALIZATION METHODS AND TOOLS

This section briefly describes applications of the emergent methodologies collectively known as the MARMAP System for landscape health assessments (Patil 2000; Patil 2001b,c,d; Patil 2002a,b,c. Also see http://www.stat.psu.edu/~gpp/newpage11.htm).

Modeling and Simulation of Thematic Raster Maps

A raster map depicts the landscape as a grid of uniform cells. Modeling and simulation of raster maps are employed for three general purposes. First, model fitting provides a set of estimated parameter values characterizing the spatial structure of the map (landscape). Second, simulation yields statistical confidence capability as well as response sensitivity to variation in the fitted parameter values. Third, model validation provides a check on tendencies to overfit the model. Three classes of map models are relevant: (A) Disjunctive Indicator Geostatistical (DIG) Model; (B) Hierarchical Markov Transition Matrix (HMTM) Model; and (C) Markov Random Field (MRF). DIG enables us to analyze (categorical) landscape condition mappings for vicinity influences to better understand the dynamics of health effects in space and time. HMTM helps us to sort out the effects of ecosystem health influences operating at different scales. MRF provides insights into the scope of variability that can occur without a fundamental change in basic landscape pattern, i.e., temporal shifts in occurrence of sustainable pattern elements.

These address issues important to monitoring and diagnostics, such as a need to determine and discriminate differing status with regard to degradation of habitat integrity across landscapes. From land cover maps derived by remote sensing, we examine naturalistic versus more strongly human disturbed situations through an index of conditional entropy to obtain profiles of disruption. This is illustrated in terms of watersheds (Figure 1) for Pennsylvania, wherein naturalistic cover would be predominantly closed forest. Profiles (Figure 1) support recognition of increasing disruption from mostly forest to partially forest to largely deforested. The profiles themselves are parameterized to provide comprehensive representations of patch structure across scaling domains. Conditional simulation is informative with regard to the effect of spatial pattern on estimation of error matrix and associated parameters for assessing accuracy of thematic mappings that constitute the basis for landscape inquiry.

For more information, see Johnson (1999), Johnson & Patil (1998), Johnson *et al.* (2001a), O'Neill *et al.* (1996), Patil *et al.* (2000a,b), and Patil & Taillie (1999; 2000a,b,c).

ECHELONS OF SPATIAL VARIATION

Echelons frame local values of synoptically mapped environmental indicators in A regional context for comparative purposes and objective analysis of complex hierarchies in spatial variation across landscapes. The environmental indicators are considered as surface variables in virtual (or real) topographies as depicted in Figure 2. Echelons are structural entities consisting of

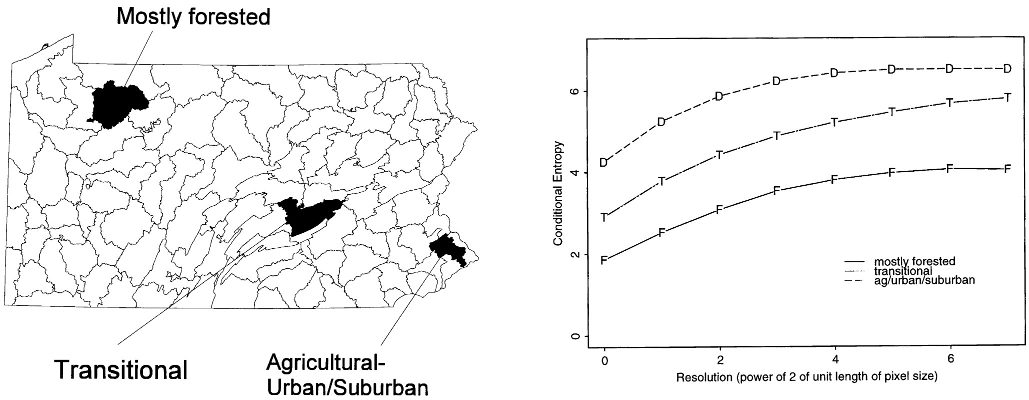

FIGURE 1. Fragmentation profiles for three Pennsylvania watersheds with distinct land cover patterns: mostly forested, transitional, and mostly deforested (agriculture/urban/suburban).

peaks, foundations of peaks, foundations of foundations, and so on in an organizational hierarchy. It is natural to cast the echelon hierarchy as a dendrogram from which profiles of spatial complexity can be obtained and "principal families" determined as contiguous areas of criticality from perspectives of either pronounced ecosystem health or pronounced ecosystem distress. Echelons have proven effective for elucidating concentration and connectivity of biodiversity, complexity of landscape change induced by factors such as wildland fire, pattern of propagation for urban sprawl, etc. (Myers *et al.* 1999; Kurihara *et al.* 2000; Smits & Myers 2000; Patil & Myers 2002).

Contemporary study of human disease as a component of ecosystem health entails a spatial scan statistic (Kulldorff & Nagarwalla 1995) for detecting geographic clusters of disease and other responses that are substantially elevated with respect to the regional setting. In conjunction with the spatial scan statistic (SATSCAN), echelon analysis can more clearly delineate zones of elevated intensity for focus of investigation (Patil & Taillie 2001d).

PATTERN-BASED LANDSCAPE CHANGE ANALYSIS

Landscape change analysis is becoming increasingly important for ecosystem monitoring. Deforestation, habitat fragmentation, and land-use conversion are growing concerns for conservation, landscape ecology, and planning. Long-term effects of global climate change are expressed in broad-area change of landscape patterns. Factoring the influences of localized human activity from broader scale changes induced by climatic effects is a major analytical challenge that cannot be addressed well until consistent methods for detecting change are available. Remote sensing data at different scales acquired by a variety of sensors are increasing rapidly in their availability. Effec-

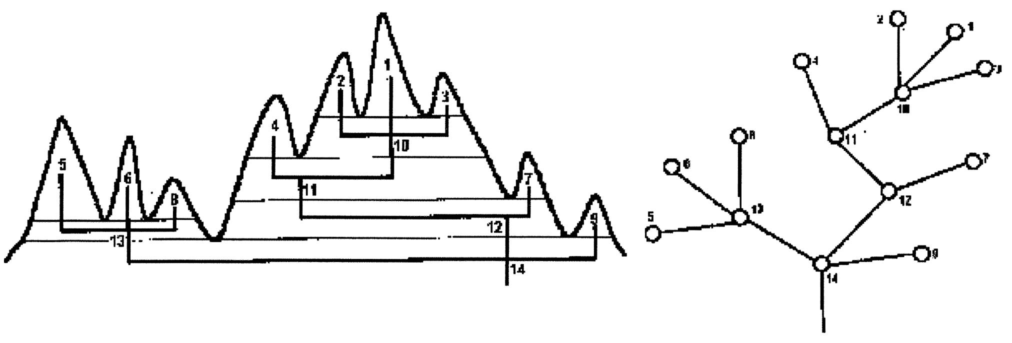

FIGURE 2. (a) Echelon decomposition of a surface and (b) associated echelon tree.

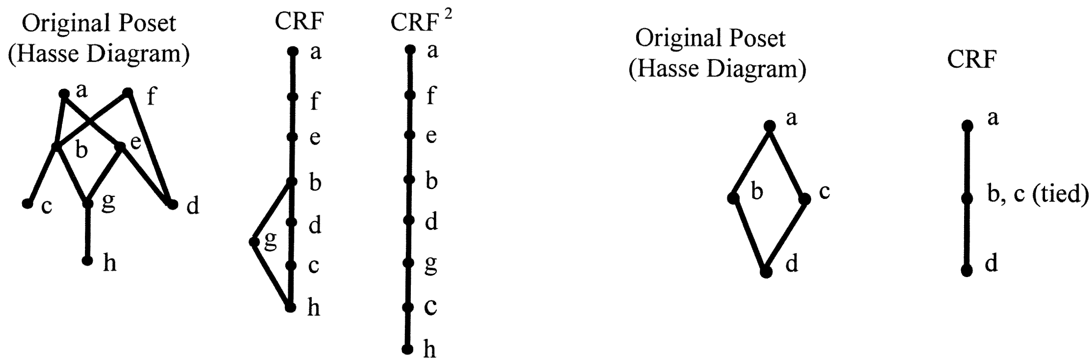

FIGURE 3. The three diagrams on the left show the linearizing effect of the CRF operator. The two diagrams on the right show how ties can emerge during linearization. A poset is a partially ordered set.

tive and parsimonious methods are needed to make the combinatorial challenges of comparative analysis manageable. It also will become necessary to accomplish comparative analysis of data from different sensors. Composite mosaics of multiple images derived by pattern-based segmentation have proven particularly advantageous for extracting and representing change from remotely sensed image sequences, where previously analysis was largely restricted to consideration of image pairs taken at two times with the same sensor (Myers 2000; Patil *et al.* 2000b).

MULTIPLE INDICATORS, PARTIAL ORDERINGS, AND MULTICRITERION DECISION SUPPORT

To prioritize and rank means to linearize. Rather than derive a composite index, we will prioritize without having to integrate the indicators. This is now possible, and the approach is relatively novel and innovative. We have developed it for nationwide prioritization for the United Nations Environment Programme (UNEP) with land, air, and water indicators measuring the human environment interface at a national level (Patil & Taillie

	Techniques/Regions	DIG	HMTM	MRF	ECHELON	POSET	SATSCAN	PSI	HSA	MCSSG	DSAMG	IDVT	GQM
		1	2	3	4	5	6	7	8	9	10	11	12
	Prototype Case Studies												
1	Pennsylvania	x	x	x	x	x	x	x	x	x	x	x	x
2	Mid-Atlantic	x	x	x	x	x	x	x	x	x	x	x	x
3	Atlantic Slope	x	x	x	x	x	x	x	x	x	x	x	x

FIGURE 4. Matrix of case studies and quantitative techniques. DIG = Disjunctive Indicator Geostatistical model; HMTM = Hierarchical Markov Transition Matrix model; MRF = Markov Random Field model; PSI = Progressively Segmenting Images; HSA = Hierarchical Structure Analysis; MCSSG = Methodological Comparatives with Spatial Statistics and Geostatistics; DSAMG = Data Structures and Algorithms for Mining Geospatial Data; IDVT = Interface Design and Visualization Toolbox; GQM = General Quantitative Methods.

2001a). For another example, a landscape atlas published by the U.S. Environmental Protection Agency (1997) considers 33 indicators of ecological condition on 123 watersheds (7-digit HUCs) of the mid-Atlantic region and attempts to rank the watersheds using clustering and quintile-frequency methods. We address the question of ranking a collection of objects when a suite of indicator values is available for each member of the collection. The objects can be represented as a cloud of points in indicator space, but the different indicators (coordinate axes) typically convey different comparative messages, and there is no unique way to rank the objects. A conventional solution is to assign a composite numerical score to each object by combining the indicator information in some fashion. Consciously or otherwise, every such composite involves judgments (often arbitrary or controversial) about tradeoffs or substitutability between indicators.

Rather than trying to impose a unique ranking, we take the view that the relative positions in indicator space determine only a partial ordering and that a given pair of objects may not be inherently comparable. Working with Hasse diagrams of the partial order, we study the collection of all rankings that are compatible with the partial order and arrive at the ranking and prioritization as in Figure 3, using cumulative rank frequency (CRF) operator specially developed for the purpose (Patil & Taillie 2001a).

HIERARCHICAL STRUCTURE ANALYSIS

Trees and other nodal graph structures arise in the map modeling, echelons, and poset components of MARMAP. Also important is the coupling of related structures. For example, when a suite of indicators is partitioned into subgroups (e.g., stressor, integrity, socioeconomic), the Hasse diagrams have a common set of labeled nodes but (potentially) different edges. Echelon trees for different surface variables over the same geographical region have their nodes partially coupled by overlapping spatial extent (Patil & Taillie 2001c,d).

MINING GEOSPATIAL DATA

Data structures and algorithms are under investigation for exploring associations between ecosystem degradation and spatial patterns, employing higher-level models for detecting changes and finding interesting spatiotemporal patterns and trends (Rodriguez 2001).

INTERFACE DESIGN AND VISUALIZATION TOOLBOX

The main goals of MARMAP are to promote the discovery of inherent structures and patterns, enable the study of particular facets and dimensions of data, and provide means to visually assess the utility and accuracy.

MATRIX OF CASE STUDIES AND QUANTITATIVE TECHNIQUES

The matrix of Figure 4 describes the coupling of case studies with the quantitative techniques. An 'x' in a cell shows the expected coupling across case studies and quantitative techniques. The prototype case studies of Pennsylvania, the mid-Atlantic region, and the Atlantic Slope are given.

6. INTEGRATION OF RESEARCH, EDUCATION, AND TECHNOLOGY TRANSFER

An essential part of this proposed methodology is to introduce concepts and methods at the core of MARMAP to researchers in ecology, environment, socioeconomics, and quality of human life. It is timely to think of multidisciplinary groups for ecosystem health measurement at the landscape level.

We have described both the challenges (Sections 1-3) and the opportunities to meet those challenges using advanced statistical and mathematical techniques (Sections 4-5). Pilot studies employing these methodologies include the U.S. Atlantic Slope and mid-Atlantic region. The experiences gained from these studies feed back into refinements of methods. At the end of the day, the thrust of this enterprise is to have quantification of ecosystem health at landscape scales, from subwatersheds to major watersheds, as an essential, replicable method of assessing our progress toward sustainability (Rapport *et al.* 1999).

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REFERENCES

Abler, D., Shortle, J., Rose, A., Oladosu, D. (2000) Characterizing the regional economic impacts of climate change. *Global and Planetary Change* **25**, 67–81.

Arrow, K., Bolin, B., Costanza, R., Dasgupta, P., Folke, C., Holling, C.S., Jansson, B.O., Levin, S., Maler, K., Perrings, C., Pimentel, D. (1995) Economic growth, carrying capacity and the environment. *Science* **268**, 520–521.

Bockstael, N. (1996) Modeling, economics, and ecology: The importance of a spatial perspective. *American Journal of Agricultural Economics* **78**, 1168–1180.

Brooks, R., Brinson, M., Hershner, C., Shortle, J., Whigham, D. (2001) *Development, Testing, and Application of Indicators for Integrated Assessment of Ecological and Socioeconomic Resources of the Atlantic Slope in the Mid-Atlantic.* Penn State Cooperative Wetlands Center, University Park, PA.

Brooks, R.P., O'Connell, T.J., Wardrop, D.H., Jackson, L.E. (1998) Towards a regional index of biological integrity: the example of forested riparian ecosystems. *Environment Monitoring and Assessment* **51**, 131–143.

Conforth, I. (1997) Selecting indicators for assessing sustainable land management. *Journal of Environmental Management* **56**, 153–179.

Costanza, R., Mageau, M., Norton, B., Patten, B.C. (1998a) What is sustainability? In: Rapport, D., *et al.* (eds) *Ecosystem Health.* pp. 31–139. Blackwell Science, Malden, MA.

Costanza, R., Mageau, M., Norton, B. and Patten, B.C. (1998b) Predictors of ecosystem health. In: Rapport, D. *et al.* (eds) *Ecosystem Health.* pp. 140–250. Blackwell Science, Malden, MA.

Daily, G. (ed) (1997) *Nature's Services: Societal Dependence on Natural Ecosystems.* Island Press, Washington, DC.

Deacan, R., *et al.* (1998) Research trends and opportunities in environmental and resource economics. *Environmental and Resource Economics* **11**, 383–397.

Deller, S., Tsai, T., Marcouiller, D., English, D. (2001) The role of amenities in rural economic growth. *American Journal of Agricultural Economics* **83**, 352–365.

Environmental Monitoring and Assessment Program (2000) *Mid-Atlantic Highlands Streams Assessment.* Final Report. EPA-903-R-00-015. U.S. Environmental Protection Agency, Washington, D.C.

Epstein, P.R. & Rapport, D.J. (1996) Changing coastal marine environments and human health. *Ecosystem Health* **2**, 166–176.

Geoghegan, J., Pritchard, L. Jr., Ogneva-Himmelberger, Y., Chowdhury, R.R., Sanderson, S., Turner, B.L.II. (1998) "Socializing the pixel" and "pixelizing the social" in land-use and land-cover change. In: Liverman *et al.* (eds) *People and Pixels. Linking Remote Sensing and Social Science.* pp. 51–69. National Academy Press, Washington, D.C.

Hilden, M. & Rapport, D.J. (1993) Four centuries of cumulative impacts on a Finnish rier and its estuary; an ecosystem health approach. *Journal of Aquatic Ecosystem Health* **2**, 261–275.

Horan, R., Hubrovcak, J., Shortle, J., Bulte, E. (2000) Green accounting with distributional weights. *Environment and Development Economics* **5**, 95–108.

Johnson, G.D. (1999) *Landscape Pattern Analysis for Assessing Ecosystem Condition: Development of a Multi-Resolution Method and Application to Watershed Delineated Landscapes in Pennsylvania.* Ph.D. Thesis. Penn State University, University Park, PA.

Johnson, G.D. & Patil, G.P. (1998) Quantitative multiresolution characterizations of landscape patterns for assessing the status of ecosystem health in watershed management areas. *Ecosystem Health* **4**, 177–187.

Johnson, G.D., Myers, W.L., Patil, G.P., Taillie, C. (2001a) Fragmentation profiles for real and simulated landscapes. *Environmental and Ecological Statistics* **8**, 5–20.

Johnson, G.D., Myers, W.L., Patil, G.P. (2001b) Predictability of surface water pollution loading in Pennsylvania using watershed-based landscape measurements. *Journal of the American Water Resources Association* **37**, 821–835.

Johnson, G.D., Brooks, R.P., Myers, W.L., O'Connell, T.J., Patil, G.P. (2002) Predictability of bird community-based ecological integrity, using landscape measurements. In: Rapport, D., Lasley, W., Rolston, D., Nielsen, O., Qualset, C., and Damania, A. (eds) *Managing for Healthy Ecosystems.* In press. Lewis Press, Boca Raton, FL.

Kulldorff, M. & Nagarwalla, N. (1995) Spatial disease clusters: detection and inference. *Statistics in Medicine* **14**, 799–810.

Kurihara, K., Myers, W.L., Patil, G.P. (2000) Echelon analysis of the relationship between population and land cover patterns based on remote sensing data. *Community Ecology* **1**, 103–122.

Mageau, M.T., Costanza, R., Ulanowicz, R.E. (1995) The development and initial testing of a quantitative assessment of ecosystem health. *Ecosystem Health* **1**, 201–213.

Michalos, A. (1997) Combining social, economic and environmental indicators to measure sustainable well-being. *Social Indicators Research* **40**, 221–258.

Michener, W.K., Baerwald, T.J., Firth, P., Palmer, M.A., Rosenberger, J.L., Sandlin, E.A., Zimmerman, H. (2001) Defining and unraveling biocomplexity. *Bioscience* **51**, 1018–1023.

Myers, W.L. (2000) *PHASE-Based Broad-Area Landscape Change Analysis.* Final Report. NASA Research Project NAGS5-6713. Environmental Resources Research Institute Research Report ER2005. Penn State University, University Park, PA.

Myers, W.L., Patil, G.P., Taillie, C. (1999) Conceptualizing pattern analysis of spectral change relative to ecosystem health. *Ecosystem Health* **5**, 285–293.

Myers, W.L., *et al.* (2000) *Pennsylvania Gap Analysis Project. Leading Landscapes for Collaborative Conservation.* Final Report. U.S. Geological Survey Gap Analysis Program.

O'Connell, T.J., Jackson, L.E., Brooks, R.P. (1998) A bird community index of biotic integrity for the Mid-Atlantic Highlands. *Environment Monitoring and Assessment* **51**, 145–156.

O'Connell, T.J., Jackson, L.E., Brooks, R.P. (2000) Bird guilds as indicators of ecological condition in the central Appalachians. *Ecological Applications* **10**, 1706–1721.

O'Neill, R.V., Hunsaker, C.T., Timmins, S.P., Jackson, B.L., Jones, K.B., Riitters, K.H., Wickham, J.D. (1996) Scale problems in reporting landscape pattern at the regional scale. *Landscape Ecology* **11**, 169–180.

Patil, G.P. (2002a) Overview of landscape ecosystem health assessment using remote sensing data. In: Rapport, D., Lasley, W., Rolston, D., Nielsen, O., Qualset, C., Damania, A (eds). *Managing for Healthy Ecosystems.* In press. Lewis Press, Boca Raton, FL.

Patil, G.P. (2002b) *Multiscale Advanced Raster Map Analysis System: Definition, Design, and Development.* Invited Paper. Joint Statistical Meetings, American Statistical Association, New York.

Patil, G. P. (2002c) Conditional entropy profiles for multiscale landscape fragmentation and environmental degradation. In: El-Shaarawi, A. & Piegorsch, W. W. (eds) *Encyclopedia of Environmetrics.* Vol. 1. pp. 413–417. Wiley, New York, NY.

Patil, G.P. & Myers, W.L. (1999) Editorial: Environmental and ecological health assessment of landscapes and watersheds with remote sensing data. *Ecosystem Health* **5**, 221–224.

Patil, G. P. & Myers, W. L. (2002) Echelon analysis. In: El-Shaarawi, A. & Piegorsch, W. W. (eds) *Encyclopedia of Environmetrics.* Vol. 2. pp. 583–586. Wiley, New York, NY.

Patil, G.P. & Taillie, C. (2001a) *On Quantitative Formulation of Nationwide Human Environment Index.* Final Report. Division of Early Warning and Assessment, United Nations Environment Programme, New York, NY.

Patil, G. P., Taillie, C. (2001b) A multiscale hierarchical Markov transition matrix model for generating and analyzing thematic raster maps. *Environmental and Ecological Statistics* **8**, 71–84.

Patil, G.P. & Taillie, C. (2001d) Powerpoint Presentations. Available at: http://www.stat.psu.edu/~gpp.

Patil, G.P., Johnson, G.D., Myers, W.L., Taillie, C. (2000a) Multiscale statistical approach to critical-area analysis and modeling of watersheds and landscapes. In: Rao, C. R. & Szekely, G. J. (eds) *Statistics for the 21st Century: Methodologies for Applications of the Future.* pp. 293–310. Marcel Dekker, New York, NY.

Patil, G.P., Myers, W.L., Luo, Z., Johnson, G.D., Taillie, C. (2000b) Multiscale assessment of landscapes and watersheds with synoptic multivariate spatial data in environmental and ecological statistics. *Mathematical and Computer Modeling* **32**, 257–272.

Pickett, S. & Rogers, K. (1997) Patch dynamics: The transformation of landscape structure and function. In: Bissonette, J. (ed) *Wildlife and Landscape Ecology.* Springer-Verlag, New York, NY.

Polasky, S., Camm, J., Garber-Yonts, B. (2001) Selecting biological reserves cost-effectively: An application to terrestrial vertebrate conservation in Oregon. *Land Economics* **77**, 68–78.

Rapport, D.J., Regier, H.A., Hutchinson, T.C. (1985) Ecosystem behavior under stress. *The American Naturalist* **125**, 617–640.

Rapport, D.J. & Whitford, W.G. (1999) How ecosystems respond to stress: Common properties of arid and aquatic systems. *BioScience* **49**, 193–203.

Rapport, D.J., Hilden, M., Weppling, K. (2000) Restoring the health of the earth's ecosystems: A new challenge for the earth sciences. *Episodes* **23**,12–19.

Rapport, D.J., Christensen, N., Karr, J.R., Patil, G.P. (1999) The centrality of ecosystem health in achieving sustainability in the 21st century: Concepts and new approaches to environmental management. *Transactions of the Royal Society of Canada,* Series VI, Volume IX. pp. 3–40. University of Toronto Press, Toronto, Canada.

Rapport, D.J., Costanza, R., Epstein, P., Gaudet, C., Levins, R. (eds) (1998) *Ecosystem Health.* Blackwell Science, Oxford, UK.

Rodriguez, S. (2001). *Statistical Data Mining of Remote Imagery for Characterization, Classification and Comparison of Landscape and Watersheds of Pennsylvania.* Ph.D. Thesis. Penn State University, University Park, PA.

Shortle, J. & Horan, R. (2001) The economics of nonpoint pollution. *Journal of Economic Surveys* **15**, 255–290.

Smits, P.C. & Myers, W.L. (2000) Echelon approach to characterize and understand spatial structures of change in multi-temporal remote-sensing imagery. *IEEE Trans. Geoscience and Remote Sensing* **38**, 2299–2309.

U.S. Environmental Protection Agency (1997). *An Ecological Assessment of the United States Mid-Atlantic Region. Office of Research and Development.* EPA/600/R-97/130. U.S. Environmental Protection Agency, Washington, DC.

Vernberg, W., Scott, G., Stozier, S., Bemiss, J., Daugomah, J. (1997) The effects of urbanization on human and ecosystem health. In: Vernberg, F., Vernberg, W., Siewicki, T. (eds.) *Sustainable Development in the Southeastern Coastal Zone.* In press. University of South Carolina Press, Columbia, SC.

Vitousek, P.M., Mooney, H.A., Lubchenco, J., Milillo, J.M. (1997) Human domination of earth's ecosystems. *Science* **277**, 494–499.

Wichert, G. & Rapport, D.J. (1998) Fish community structure as a measure of degradation and rehabilitation of riparian systems in an agricultural drainage basin. *Environmental Management* **22**, 425–443.

Wu, J. (2001) Environmental amenities and the spatial pattern of urban sprawl. *American Journal of Agricultural Economics* **83**, 691–697.